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for X-Ray Lithography and X-Ray Radiography**

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A Simple, Compact, High Brightness Source for X-Ray Lithography and X-Ray Radiography*

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Abstract

A simple, compact, high brightness x-ray source has recently been built. This source utilizes a commercially available, cylindrical geometry electron beam evaporator, which has been modified to enhance the thermal cooling to the anode. Cooling is accomplished by using standard, low-conductivity laboratory water, with an inlet pressure of less than 50 psi, and a flow rate of approximately 0.3 gal./min. The anode is an inverted cone geometry for efficient cooling. The x-ray source has a measured sub-millimeter spot size (FWHM). The anode has been operated at 1 KW e-beam power (10 KV, 100 ma). Higher operating levels will be investigated. A variety of different x-ray lines can be obtained by the simple interchange of anodes of different materials. Typical anodes are made from easily machined metals, or materials which are vacuum deposited onto a copper anode. Typically, a few microns of material is sufficient to stop 10 KV electrons without significantly decreasing the thermal conductivity through the anode. The small size and high brightness of this source make it useful for step and repeat exposures over several square centimeter areas, especially in a research laboratory environment. For an aluminum anode, the estimated Al-K x-ray flux at 10 cms. from the source is $70 \mu\text{M}/\text{cm}^2$.

Introduction

Compact, bright and simple to operate x-ray sources are useful for a variety of reasons, including x-ray lithography and radiography. In the following paper, we describe an electron-beam excited x-ray source which is useful, especially in a research environment. The source has a small, sub-millimeter, spot size and is relatively bright. In addition, it is simple to maintain, and inexpensive to build.

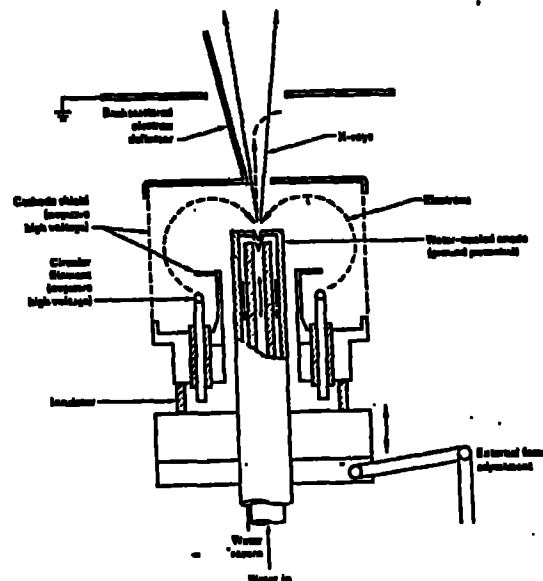
It is clear that there is much interest in a high power, bright x-ray source which can be commercially used for x-ray lithography. These sources include "gas-puffs," laser produced plasmas¹ and more conventional electron beam sources. During the past few years, high power electron beam sources have become commercially available² but are often prohibitive in cost for research environments. However, recent developments at LLNL have shown that it is possible to build an inexpensive conventional source and obtain the x-ray brightness similar to that of a more expensive systems. The source that we have built is water cooled with standard (1 M-cm) laboratory water, at relatively low inlet water pressure (50 psi), and flow rate (20 cc/sec). The anode is interchangeable so that different x-ray lines can be obtained by using different x-ray anodes.

The X-Ray Source

The x-ray source is a modified commercially available electron beam evaporator, available from VG Instruments.³ The evaporator is cylindrically symmetric, and runs with the filament at high negative potential. Two cathode shields, also biased at a high negative potential, focus the electrons to the grounded anode (Fig. 1). Under proper mechanical focussing, it is possible to focus electrons from the filament to a spot of approximately 1 mm on the anode. Previous work has already demonstrated this source for x-ray lithography by replacing the electron beam hearth with either a carbon or copper anode, and adding an electron deflector to deflect any backscattered electrons away from the exposed wafer.⁴ Recent modifications have made it possible to use an interchangeable anode (Fig. 2), and increase the thermal loading on the anode by using an inverted cone (Fig. 3). (All anodes to date are machined from copper for high heat conductivity, and different x-ray line emission is obtained by coating a copper anode with 10-20 microns of material, such as aluminum, silver, etc.) Additionally, the original electron beam evaporator was designed to operate vertically, and both parts of the cathode shield assembly were held by gravity. To operate the source either horizontally or inverted, we "tack-welded" the inner cathode shield to its support, and held the outer cathode shield in place with three small set-screws.

To electrically drive the x-ray source, we used a high voltage power supply plus a filament transformer (Fig. 4). By overdriving the filament (approximately 30 amps), the emission current is saturated, so that it is virtually insensitive to thermal drifts in the filament, and the emission is stable. In addition, by varying the geometry of the inner cathode shield, it is possible to change the saturated emission current for a given gun voltage (Fig. 5). Therefore, the optimum gun voltage for a fixed power, loading can be chosen for a particular x-ray anode. For example, to optimize the emission from an aluminum anode ($\text{AlK} = 1.5 \text{ KeV}$), we would operate at approximately three times the ionization potential, or roughly 4.5 KV. For a maximum thermal load of 1 KW, we desire 220 ma emission current, which requires a value of $X = 22 \text{ mm}$ for the inner cathode shield. Alternatively, a 1 KW loaded chromium anode ($\text{CrK} = 5.4 \text{ KeV}$) should be run at 16 KV, 60 ma and $X \sim 26 \text{ mm}$.

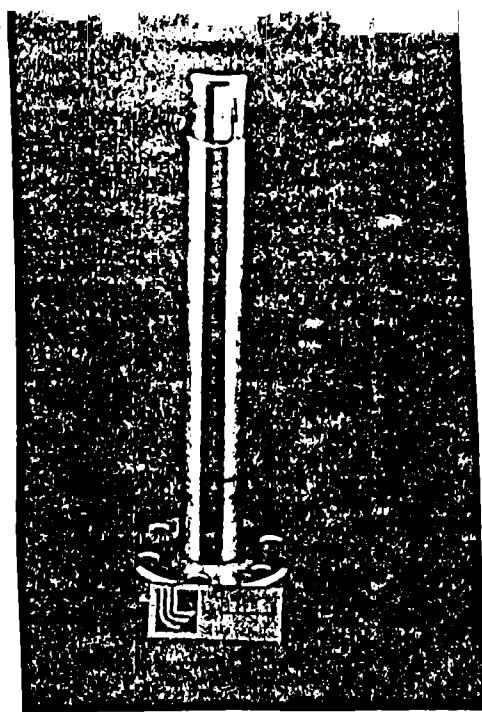
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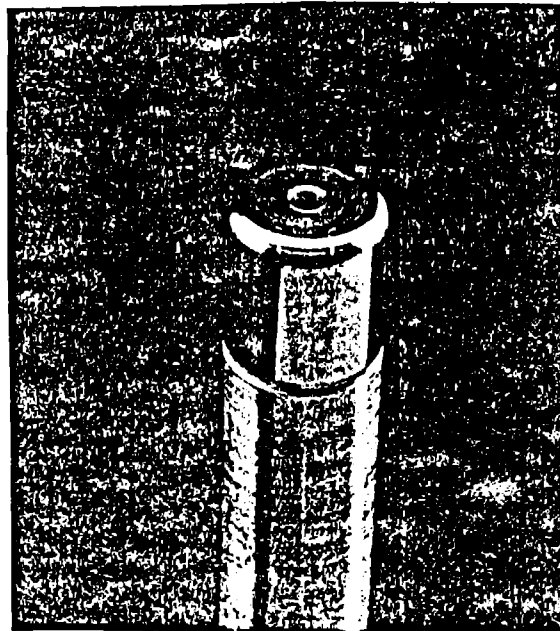
1. A line drawing illustrating the cylindrically symmetric, x-ray source. The cathode shields deflect the electrons from the filament onto the water cooled anode. An external mechanical adjustment focusses the source by sliding the cathode shield up and down.

Thermal Loading

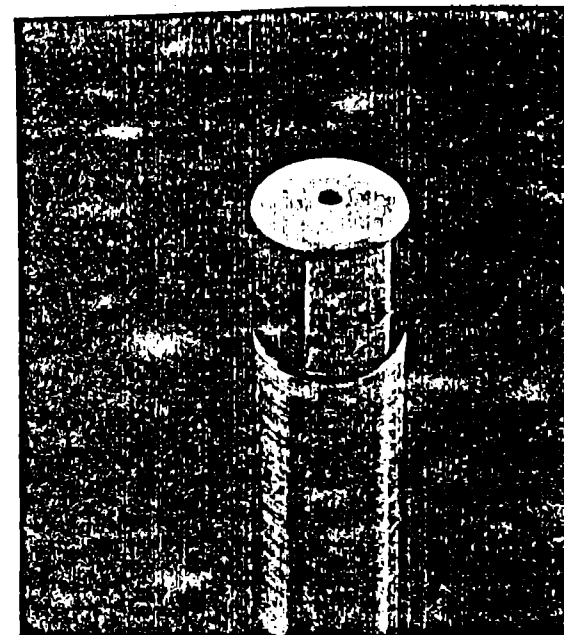
To increase the brightness of the source, it is necessary to increase the permissible thermal loading on the anode. One of the most thermally conductive (and easily machinable) materials is copper, but according to Müller² the maximum e-beam thermal load for copper in a 1 mm spot size is 892 watts before the copper melts. A reasonable, safe limit is approximately 400 watts. To increase this limit, two modifications were incorporated: first, the anode is thin walled and water cooled; and second, the anode is designed with an inverted cone. The inverted cone (Fig. 3) increases the copper cross-sectional area to the electron heating by approximately four times that compared to a planar anode with an equivalent projected x-ray source size. The high take-off angle reduces the x-ray flux onto the sample³ but the total effect of the inverted cone still increases the x-ray flux onto the sample for cones with included angles $\geq 30^\circ$. In addition, the thin walled, water cooled anode efficiently removes the 1 KW of e-beam power deposited on the anode. Since the water cools a grounded anode, no special precautions are needed to prevent either electro-chemical reactions or electrical arcing in the water. Normal operating conditions require approximately 20 cc/sec of 1 M Ω -cm laboratory water flowing through the anode (with an inlet pressure of 50 psi). Under steady state conditions, calculations indicate that the average water temperature is raised by approximately 15° C, however, since only some of the water actually comes in contact with the inverted cone, a fraction of the water boils. This boiling actually increases the efficiency which the water can remove the heat from the anode because it breaks-up any laminar-flow layer along the copper surface.



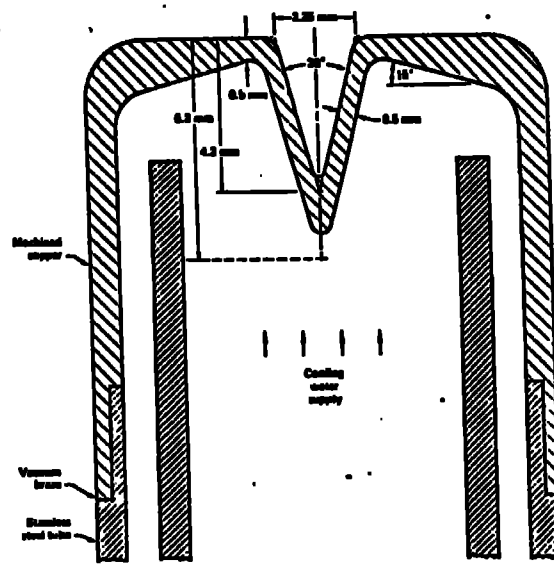
2a. A picture of the anode mounted on a vacuum flange. Different x-ray emission can be obtained by replacement with an anode made from, or overcoated with, different material.



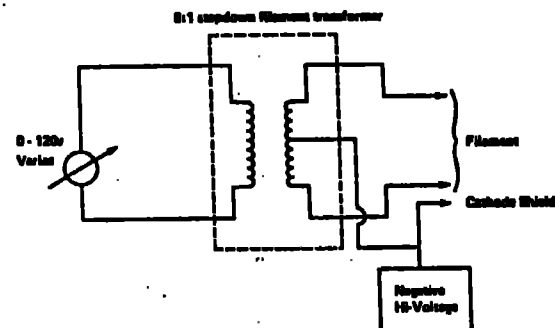
2b. The machined, inverted cone-shape, copper anode.



2c. Same as 2b, except coated with 20 microns of aluminum.



3. A schematic illustration of the inverted cone design used for this work.



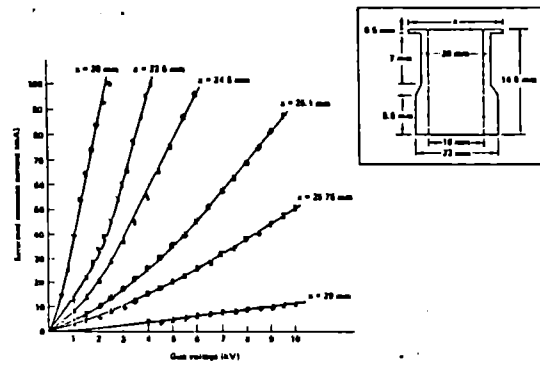
4. A line drawing of the high-voltage electronics used to drive this source.

To maximize the thermal loading on the anode, the anode material must be made of high thermal conductivity material. Copper was chosen as our anode material, and to change x-ray line emission, 10-20 microns of material can be deposited onto the copper anode. 10 keV electrons are effectively stopped by this deposited layer, and few electrons actually penetrate the deposited overcoat and excite copper x-rays. As a result, the x-rays emitted from this anode are the typical line emissions from the overcoat. The thermal conductivity of this thin deposited layer does not severely affect the overall thermal conductivity of the anode. In Table 1, the thermal conductivity of many common materials are listed, and calculations indicate that the effective thermal conductivity of the copper with an overcoat is not significantly decreased from the thermal conductivity of the base copper for overcoats less than 20 microns thick and thermal conductivities greater than 50 W/met-°K. As a result, many different materials can be used as an overcoat to generate various x-ray line emissions.

X-Ray Detection and Source Characterization

For both x-ray imaging and spectroscopic measurement of the anode emission, an x-ray charged coupled device (CCD) was used.⁸ The front illuminated, virtual phase CCD chip, made by Texas Instruments, Inc., has a 390 x 584 pixel array (2×10^5 pixels). Since each pixel is 22 microns square, the total active area is 8.6 x 12.8 mm. The pixel capacity is 4×10^5 electrons, and the CCD is sensitive to x-ray photons with energies from 0.5 to 15 KeV. An incident photon produces hole-electron pairs, and the number of electrons trapped in a pixel is linearly dependent upon the number of x-ray photons and the x-ray energy incident upon the pixel. For imaging purposes, we can use all or part of the 398 x 584 array. The number of electrons recorded in each pixel is then displayed on a CRT.

An x-ray pinhole camera, utilizing a 10 micron pinhole, was used to produce a 5 times magnified image of the source onto the CCD chip. The source operating conditions could then be varied to determine source size effects in real time. Both external mechanical focusing of the cathode shield assembly and accelerating gun voltage were varied, and both were seen to have a large effect on the x-ray source size. At operating voltages less than 4 KV, the source was annular, and it was impossible to obtain a single spot for the source emission, Fig. 6. However, at voltages greater than 6 KV, it was possible to focus the electrons deep into the anode cone, and obtain a single, bright spot, Fig. 7. The measured FWHM of the source in Fig. 7 is approximately 0.5 mm.

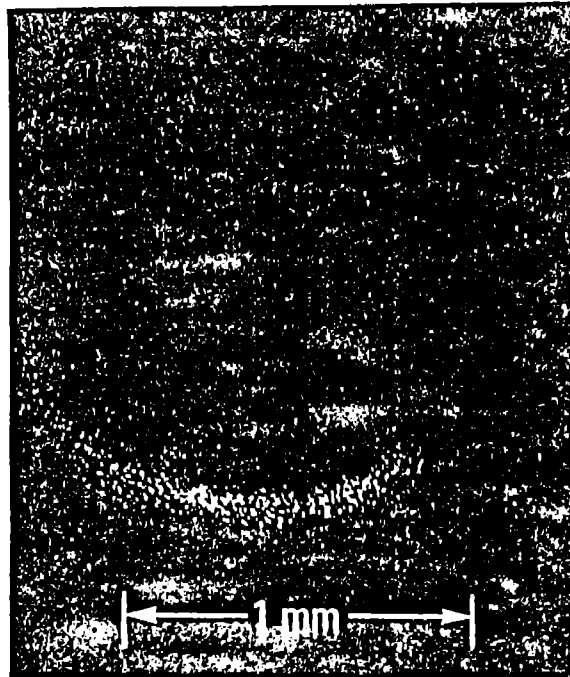


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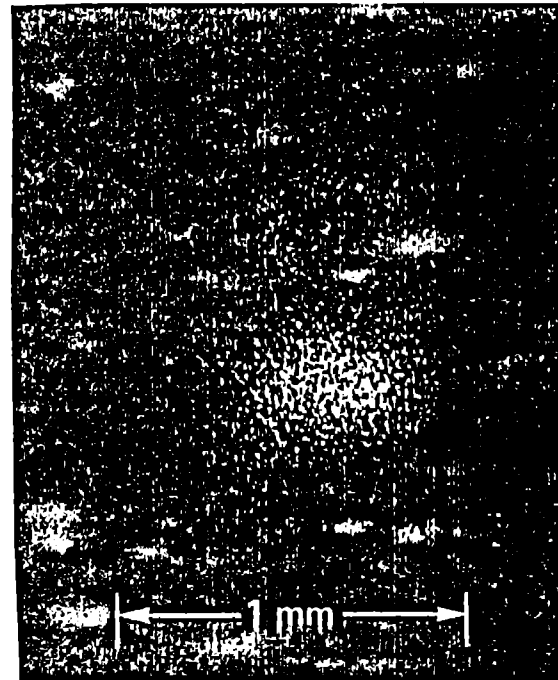
TABLE 1
Thermal Conductivities of Selected Materials⁷

Material	Thermal Conductivity (W/met-°K)
Cu	393
Al	234
Be	172
Au	313
Ag	422
Si	150
Ge	50
Graphite	5-580

5. Saturated emission current versus cathode shield geometry.



6. An x-ray pinhole image of the source operating under best focus and with an accelerating voltage of 4 kV.



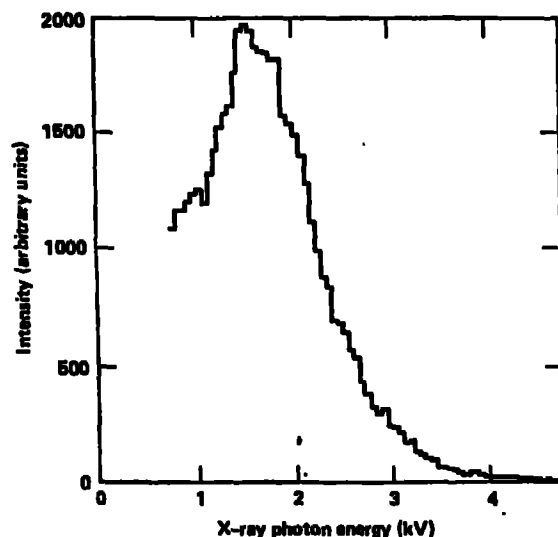
7. An x-ray pinhole image of the source operating under best focus and with an accelerating voltage of 8 kV.

The x-ray CCD can also be used for spectroscopic measurements. Under low flux conditions, such that only one x-ray photon is incident per CCD pixel, the number of recorded electrons in the pixel is directly related to the x-ray photon energy. A histogram of the number of electrons recorded in a single pixel versus the number of pixels with that value is a measurement of the x-ray spectrum. Readout noise determines the lower energy limit for this measurement which for our case is approximately 900 eV. A spectrum of the x-ray emission from the copper anode with a 4 KV accelerating voltage and filtered through a 25 micron Be foil was measured, Fig. 8a. The Cu-L lines are not seen because of the electronics noise and Be filtering. The same spectrum, but further filtered with a one micron aluminum foil, was also measured, Fig. 8b, which clearly shows the aluminum absorption edge. The x-ray emission from an anode coated with 20 microns of aluminum and with 5 KV accelerating voltage was also measured, Fig. 9, which clearly shows the characteristic x-ray emission from an aluminum anode without any apparent Cu-L radiation.

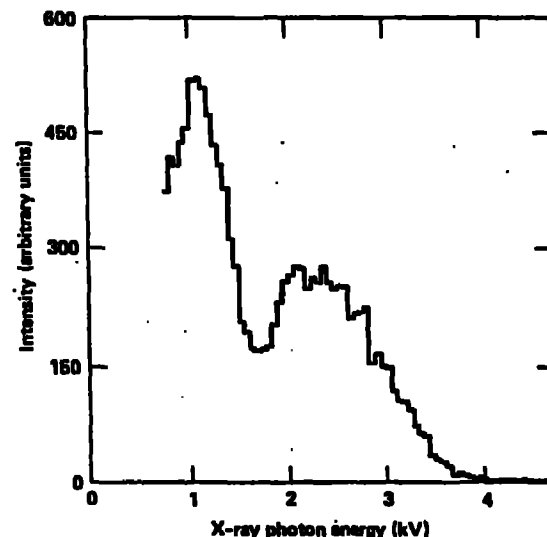
Source Brightness and X-Ray Lithography Applications

Based on the published conversion efficiency and geometry factor (take-off angle) for an aluminum anode,⁹ the A_{K} x-ray flux at 10 cms from the anode is approximately $70 \mu\text{W}/\text{cm}^2$. It is difficult to compare x-ray source brightness for different sources due to different anode materials and take-off angles. However, a reasonable figure of merit is the electron beam power loading on the anode, relative to the x-ray source size in Watts/cm². For example, the source described in this paper can operate at 1 KW e-beam loading, and the x-ray emission indicates a sub-millimeter source size, producing a figure of merit of approximately $1 - 3 \times 10^4 \text{W}/\text{cm}^2$. (It appears that this anode can handle more thermal loading, but this has not been experimentally verified.) Other x-ray sources, along with their characteristics, are listed in Table 2. As can be seen, the figure of merit indicates that this source is competitive with many other, more complex systems, although it should be pointed out that if total energy is the only criterion (rather than source brightness), then the Rigaku rotating anode system is the most intense. What makes the source described in this paper particularly attractive is its simplicity, ease of operation and low cost.

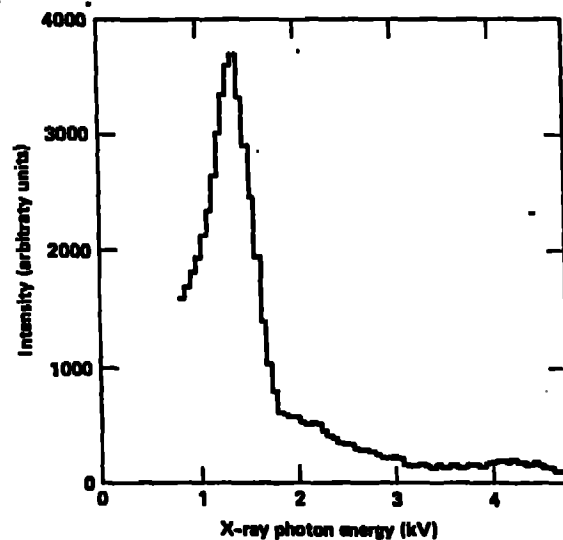
Recently, the first x-ray replication using this system was performed. A copper anode, operating at 4 KV and 70 ma (280 Watts), was used. The mask was a free standing thick (>1 micron) gold zone plate pattern, and was in intimate contact with a 2 inch diameter silicon wafer, coated with 1 micron of PMMA. The source to sample distance was 15 cms, and the exposure time was 8 hours. After 45 seconds of development in 60% MIBK, 40% IPA, the sample was clearly over developed, indicating that the exposure time can be reduced. We estimate that using PMMA as our resist and with a 10 cm source to sample distance, exposure times of 1 hour are achievable using a Cu anode operating at 1 KW e-beam power. SEM micrographs of the exposed pattern were not available at publication time, but will be shown at the meeting.



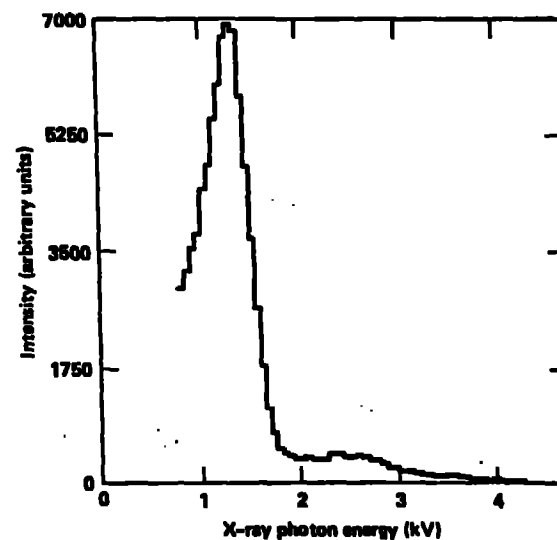
8a. The measured spectrum emitted from a copper anode, with a 4 KV accelerating voltage. A 25 micron Be foil was used as a filter between the source and the CCD.



8b. Same as 8a except with an additional 1 micron Al filter between the source and the CCD.



9a. The measured spectrum emitted from a copper anode overcoated with 20 microns of aluminum, and with a 5 KV accelerating voltage. A 25 micron Be foil was used as a filter between the source and the CCD. Notice the characteristic aluminum emission



9b. Same as 9a, except with an additional 1 micron Al filter between the source and the CCD.

Table 2
Comparison of Different Sources

Source	e-beam Power Loading	X-Ray Source Size	e-beam Power Density on Anode (W/cm ²)
Rigaku Ru-1500	90 KW	1 x 10 mm	9×10^{10}
Kevex ¹⁰	4.5 KW	Annulus: 3 mm OD ~1 mm ID	7×10^9
HP ¹¹	>6.2 KW	Annulus: 3 mm OD ~1 mm ID	$>10^9$
Maldonado ¹²	4-8 KW	3 mm diameter	$5 \times 10^9 - 1 \times 10^{10}$
Gaines ¹³	3 KW	3-15 mm diameter	$2 \times 10^9 - 4 \times 10^9$
LLNL	1 KW	< 1 mm diameter	$1 - 3 \times 10^9$

Improvements

More efficient anode cooling will permit source operation at higher input powers. To achieve this, two modifications are desirable: first, the anode wall can be made thinner in the cone region, and second, the water inlet tube can be a small diameter. A thinner anode wall will allow more efficient heat transfer from the thermally loaded side of the anode to the cooling water. A smaller diameter water inlet tube would bring more of the cooling water in contact with the anode. Although these modifications are clearly beneficial, it is unclear that they are worth the effort. For example, an anode with a thinner wall is difficult to fabricate, and a small diameter inlet water tube would require higher inlet water pressure. Both of these qualities already exist in the HP x-ray source (wall thickness ≈ 125 microns, inlet water pressure = 900 psi).

Lastly, we have found that under high (1 KW) thermal loading, a 20 micron thick aluminum coating peels off from the copper base. (This does not occur at 500 W thermal loading.) We feel that this is due to the different thermal expansion coefficients between copper and aluminum. Therefore, when possible, it is advisable to use an anode base with a similar thermal expansion rate as the overcoat or to use the characteristic x-ray emission directly from the base material of the anode. The second option is clearly superior, but it is impossible to machine a vacuum tight x-ray anode out of all materials, which makes the first option (material deposited onto a base) very versatile. More efficient anode cooling, as described above, would reduce the peeling problem and allow higher power operation.

Conclusions

We have built a simple, inexpensive x-ray source and have analyzed the x-ray emission from this source. Measurements indicate that the source brightness is comparable with other sources, and the ability to easily change anodes for different x-ray line emission make the source versatile. Under some conditions, the power loading can cause the anode overcoat to peel off, but this can be reduced by more efficient anode cooling, and with a better thermal expansion rate match between the anode base and the anode overcoat.

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